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Simulation and experimental study on distortion of butt and T-joints using WELD PLANNER †

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Abstract

This paper investigates the capability of linear thermal elastic numerical analysis to predict the welding distortion that occurs due to GMAW process. Distortion is considered as the major stumbling block that can adversely affect the dimensional accuracy and thus lead to expensive corrective work. Hence, forecast of distortion is crucially needed and ought to be determined in advance in order to minimize the negative effects, improve the quality of welded parts and finally to reduce the production costs. In this study, the welding deformation was simulated by using relatively new FEM software WELD PLANNER developed by ESI Group. This novel Welding Simulation Solution was employed to predict welding distortion induced in butt and T-joints with thickness of 4 mm. Low carbon steel material was used for the simulation and experimental study. A series of experiments using fully automated welding process were conducted for verification purpose to measure the distortion. By comparing between the simulation and experimental results, it was found out that this program code offered fast solution analysis time in estimating weld induced distortion within acceptable accuracy.

Keywords: FEM; Numerical analysis; Welding distortion; WELD PLANNER

1. Introduction

Welding is extensively used as a principal method of fabricating and assembling numerous metal products such as in shipbuilding, construction, aviation and automotive industries. One popular arc welding process, gas metal arc welding (GMAW), has been applied in a wide range of plate thicknesses due to its easiness and relatively high productivity. Welding is considered as the most efficient, dependable and economical means of fabrication to join metals permanently. However, distortion is frequently encountered as a result of the welding process that adversely affects the dimensional accuracy and aesthetical value, which can lead to expensive remedial work and thus increase the fabrication costs. Distortion in a welded part occurs due to non-uniform expansion and contraction of the weld metal and adjacent parent metals, caused by complex temperature changes during the welding process. In addition, the distortion triggered from the welding process can induce residual stress as well, which significantly affects the performance of the welded structure.

Many numerical methods and experimental studies have been performed to predict welding distortions. In Ref. [1], prediction of welding deformations in butt joint of thin plates was conducted using thermo-elastic-plastic finite element methods, and comparing the results with the experimental and empirical methods. From their observation, plate thickness and welding speed have been proven to have significant effects on welding distortions. It can be seen that the longitudinal and transverse shrinkages are increased when the welding speed is reduced. Considerable decreases of the transverse and longitudinal shrinkages can be observed when the plate thickness is increased. Research based on finite element analysis using linear elastic shrinkage volume and experimental methods was performed in Ref. [2] to study the welding distortions. It was found that when the included angle of single-vee butt preparation increases, the angular distortion is increased as well. For a large welded structure, the prediction of welding distortion was done by using elastic FEM based on inherent strain theory and thermal elastic-plastic FEM [3, 4]. The elastic FEM has been proven to be faster than thermal elastic-

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Fig. 1. Robotic welding and apparatus used in experiment.

plastic FEM in predicting the welding deformation for large welded structures. The elastic FEM required only a short computational time in order to predict welding distortion accurately. Moreover, the result from this study showed that the initial gap between skin plate and stiffener is one of the factors that can contribute to welding distortion. For a thin plate structure, consideration of non-linear geometry is also important in order to precisely predict the welding deformation. For multi-pass welding analysis using specialized FEM software SYSWELD, it is very important to simulate the welding process using the suitable heat source model in order to obtain reliable results of the distortion [5]. The computational time of 3D analysis is much longer than 2D analysis; however, the simulation time is also influenced by the size of meshing element in which the coarser mesh will require lesser time consumption.

In this study, linear elastic shrinkage method using relatively new FEM software WELD PLANNER, which was developed by ESI Group, is employed to simulate the welding process and to predict the welding distortion in butt joint and T-joint with thickness of 4 mm. For verification purpose, a series of experiments were also performed using fully automated welding system with GMAW power source. The shielding gas for the welding process was a mixed gas consisting of argon (Ar) and carbon dioxide (CO_2) with 80% and 20% in composition, respectively. To measure the initial and final dimensions of the specimen, a coordinate measuring machine (CMM) was applied.

2. Experimental set up and procedure

For verification purpose, a series of experiments were carried out using robotic welding ABB IRB 2400/16 with GMAW power source KEMMPI ProEvolution ProMIG 540 MXE as illustrated in Fig. 1. Nowadays, robotic welding is recognized as a mature production method which has a flexible movement pattern using six axes. The advantage of a robotic welding system is that one single point remote robot control unit can be used to perform all welding parameters and robot programming [6].

Table 1. Welding parameters used for experimental method.

Welding parameters	Butt joint	T-joint
Current, I (A)	140 - 160	140 - 160
Voltage, V (V)	17 - 20	17 - 20
Travel speed, v (mm/s)	4	5
Wire feed speed, wfs (m/min)	3.5 – 4.0	3.5 – 4.0
Shielding gases (Ar / CO_2)	80% / 20%	80% / 20%
Weaving type	Zigzag	Zigzag

Fig. 2. Clamping conditions for butt and T-joints.

While the edges of the 4 mm low carbon steel specimens for butt joint were prepared by grooving a 60^o-included angle, the T-joint specimens were welded without edge preparation. Prior to the experiments, both plates were tacked using GTAW. Fig. 2 shows the clamping conditions during the welding process. Filler wire with AWS Classification of ER70S-6 and 1.2 mm in diameter was used throughout this study.

The welding parameters that have been used during the experiments are in Table 1. Prior to the welding process, both specimens of butt joint and T-joint were measured to gain the initial readings of specific points on the specimens. The measurement was conducted using CMM model Mitutoyo 707. After the welding process and sufficient time for cooling to room temperature, the specimens were once again measured using the same machine to obtain the final readings of the identical points that had been measured before. Then, the actual angular distortion could be defined by measuring the relative value between before and after the welding process.

3. Welding simulation method

3.1 Geometrical modeling of butt and T-joints

A schematic illustration of FE models of butt and T-joints is displayed in Fig. 3. FE mesh of butt joint has two symmetrical plates with plate size of 50 mm x 150 mm. A weld bead for the butt joint is also modeled on which the welding trajectory is located. T-joint consists of two plates, which are base plate with 100 mm x 150 mm and stiffener with 50 mm x 150 mm. Similar to butt joint, a weld bead on T-joint is also modeled and the welding trajectory is located on the bead as well. During the simulation, both butt and T-joints have different clamping conditions. The clamping conditions used in WELD

Table 2. Chemical composition of low carbon steel.

Elements (%)	DIN 17100/EN 10025	Experiments
C	Max. 0.20	0.186
Mn	Max. 1.60	0.146
Si	Max. 0.55	0.011
S	Max. 0.035	0.0011
P	Max. 0.035	0.001

Table 3. Physical properties of St52.

Properties	Values
Young's modulus (GPa)	210 (at 20°C)
Minimum yield strength (MPa)	355
Poisson's ratio, ν	0.33
Solidus temperature, TS (°C)	1404
Liquidus temperature, TL (°C)	1505

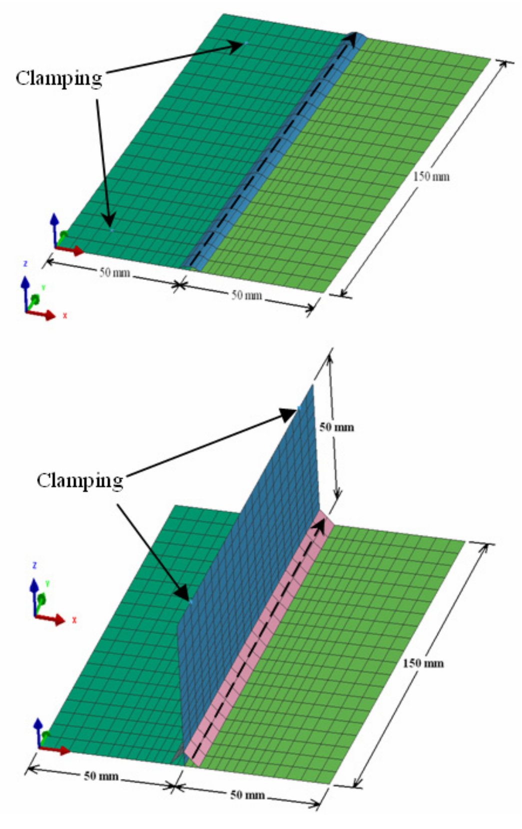

Fig. 3. Finite element models used for welding simulation.

PLANNER simulation are as exhibited in Fig. 3.

3.2 Material modeling

In this simulation, St52 (DIN 17100) or S355J2G3 (EN 10025) or low carbon steel material has been used to predict the welding distortion. This type of structural steel has been widely used in many applications, combining good welding properties with guaranteed strength. Table 2 shows the chemical composition based on the international standards and the experimental results obtained using an Arc Spark Emission Spectrometer with pure argon 99.9% and its software Spark Analyzer MX. The mechanical and thermal properties are as presented in Table 3.

3.3 Simulation method and procedures using WELD PLANNER

3.3.1 Linear elastic FE analysis

The principal relationship between heat input and weld-induced distortion has already been observed by many researchers [1-5, 7-9]. For linear elastic FE analysis, each step of the welding process is not simulated, whereas only steady-state thermal mechanical analysis is involved. Furthermore, metallurgical structure analysis is omitted. The total strain computed in this method is solely dependent on elastic strain in which the modulus of elasticity and Poisson's ratio are calculated at ambient temperature while neglecting the temperature-dependent material properties. Therefore, by using this approach, prediction can be made in a short analysis time.

The linear elastic FEA uses a simplified modeling approach with appropriate assumptions introduced as equivalent loading which should be in proportion to the induced distortion. The equivalent loading force and shrinkage deformation are formulated in FE analysis using following equation:

$$\{x\} = [k]^{-1}\{F\}. \tag{1}$$

The equivalent shrinkage force F is mainly determined by the heat input and material properties and can be calculated by using Eq. (2) [7].

$$F = Eq\alpha / c\rho \tag{2}$$

where x, F, k, E, q, α, c, and ρ denote the shrinkage value (mm), equivalent shrinkage force (N), equivalent shrinkage stiffness of the weld-affected zone (N/mm), elastic modulus (N/mm^2), heat input per unit length (J/mm), thermal expansion coefficient (°C^{-1}), specific heat capacity (J/kg°C) and density (kg/mm^3), respectively. Similarly, the relation between equivalent loading moment and distortion deformation is given by:

$$\{\theta\} = [k_o]^{-1}\{M\} \tag{3}$$

where θ denotes the angular distortion value (rad), M is the equivalent bending moment (Nmm) and k refers to the equivalent bending stiffness of the weld-affected zone (Nmm). Fig. 4 demonstrates the models of butt and T-joints welding using the approach of linear elastic FE.

3.3.2 Simulation procedures using WELD PLANNER

WELD PLANNER offers two numerical approaches for

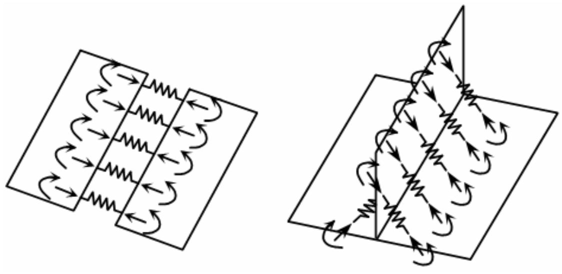

Fig. 4. Models of shrinkage forces and moments for butt joint (left) and T-joint (right).

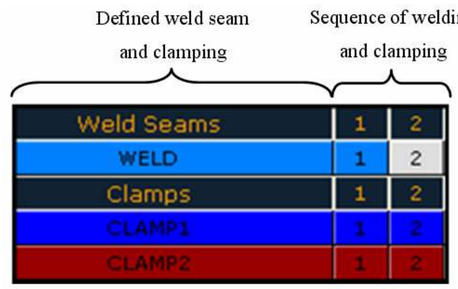

Fig. 5. Defining welding sequence and clamping condition in WELD PLANNER.

solving the weld induced distortion: linear and non linear methods. In this study, linear thermal elastic FE analysis using shrinkage method was investigated. This method, however, does not employ a moving heat source and hence allows a fast approximate evaluation of distortion without the need to compute a temperature field. This so-called steady state FE approach assumes that linear thermal contraction of weld metal when it cools down from elevated to room temperature is the major driving force for welding deformation [2].

WELD PLANNER includes the following major steps for analyzing the distortion: (1) modeling the specimen geometry and its weld bead, (2) generating weld seams and clamping conditions (manual or automatic), (3) determining the welding and clamping sequences, (4) defining the material properties, welding process and bead width, (5) selection of simulation methods (linear or nonlinear), and (6) post-processing and analyzing including visualization of the results.

The geometrical model of plates should consist of a suitable number of shell elements in transverse direction in order to cover variants in weld energy. There is no gradient available in longitudinal welding direction due to shrinkage method. The geometrical model of weld bead should be positioned within the tube and should have not less than two elements perpendicular to the welding direction. Fig. 6 presents the calibration procedure using the etched macrographs of welded specimens and the modeled weld beads used for finite element analysis. In determining the welding sequence and clamping condition, a table-look-up structure (Fig. 5) provides easy overview and determination for the user.

Fig. 5 shows an example of the sequence arrangement of welding and clamping, whereby in this scenario the workpiece is clamped during ("1") and after ("2") welding process.

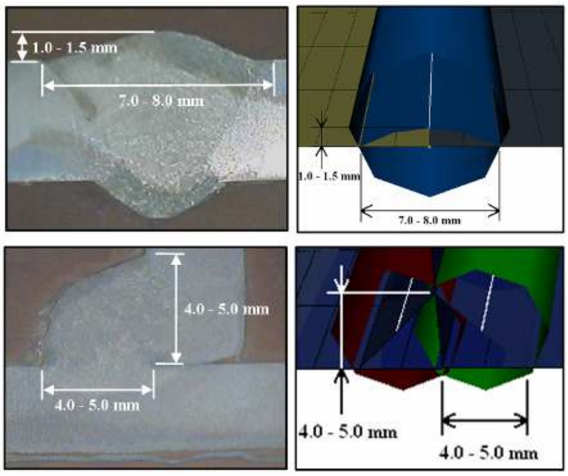

Fig. 6. Calibration procedure: etched macrographs and geometrical models for butt joint (top) and T-joint (bottom).

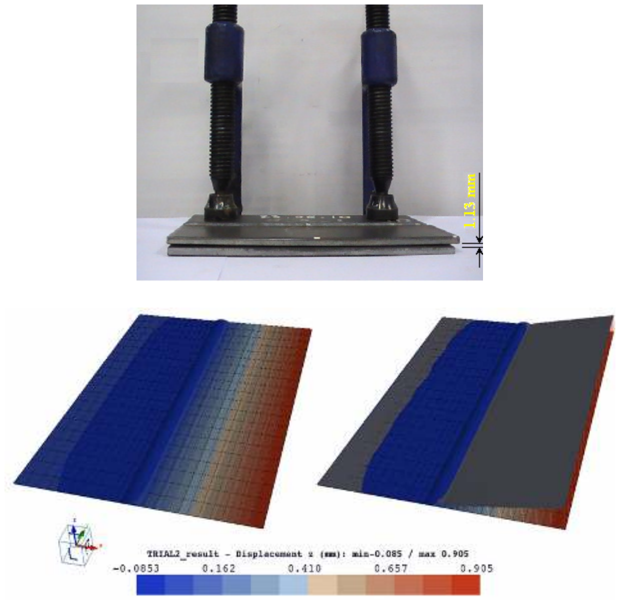

Fig. 7. Angular distortion from experiment (top), and simulation of butt joint without (below, left) and with 10x magnification (below, right).

4. Results and discussion

Figs. 7 and 8 display the predicted results of angular distortions in butt and T-joints without and with 10x magnification factor, respectively. Looking through the deformed shapes reveals that the angular distortions on base metals of butt and T-joints occurred in upward directions.

Table 4 presents the maximum values of distortions estimated through finite element simulations and also the maximum values of distortions that obtained by means of the ex-

Table 4. Comparison of angular distortion results between simulation and experimental methods.

Joint types	Simulations		Experiments		Error percentages (%)
	(mm)	(rad)	(mm)	(rad)	
Butt joint	0.90	0.018	1.13	0.023	20.4
T-joint (1st welded side)	1.11	0.022	1.38	0.028	19.6
T-joint (2nd welded side)	0.81	0.016	0.67	0.013	20.9

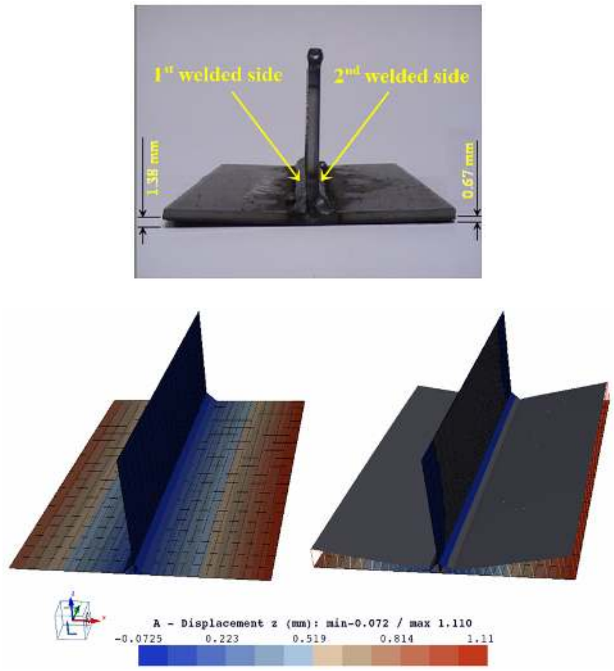

Fig. 8. Angular distortions from experiment (top), and simulation of T-joint without (below, left) and with 10x magnification (below, right).

perimental methods. From the figures in the table, it can be observed that the pattern of the predicted results is nearly similar to the experimental measurements.

5. Conclusions

Through finite element simulation and experimental study, the results from both methods revealed a reasonable agreement. The finite element analysis using linear elastic shrinkage method has been proven to show a huge potential in estimating the welding distortions sensibly. A principal advantage of using this prediction method is that only a short computational time is required for the simulation analysis. The accuracy of this method is crucially dependent on the geometrical model of weld bead. Hence, the size of weld bead should be wisely determined according to the actual weld bead in order to obtain accurate and reliable results. Conversely, the deviating results in this study might arise from other factors such as physical properties and chemical composition of materials, geometry and thickness as well. Besides, the significant contribution from this research is that the distortion which is inevitable can be predicted; thus the control of distortion can be possibly planned in advance prior to the commencement of the actual welding process. Therefore, this software possesses a great potential for identifying distortion in more complex welded joints.

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Nomenclature

I : Current
V : Voltage
v : Travel speed
wfs : Wire feed speed
x : Displacement on X axis
z : Displacement on Z axis

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